Formation of anisotropic excitation on optically bound levels with parity violation

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Interference between electric and magnetic dipole radiation results in anisotropy on degenerate levels. For spherically symmetric geometry of the distribution of light helicity results. A gas with helicity acquires inverted amplitude-dispersive properties for optomagnetic resonances in a transverse magnetic field.

The law of conservation of parity, satisfied by the electromagnetic interaction in atoms, rigorously forbids the simultaneous presence of electric and magnetic dipole ($E1$ and $M1$) transitions between any two levels. This is due to the different selection rules that govern $E1$ and $M1$ transitions and follows from the transformation properties under space inversion of the operators describing the electric and magnetic dipole interactions: $\hat{D}=-\mathbf{E}\mathbf{d}$ and $\hat{V}_M=-\mu\mathbf{H}$. $E1$ transitions are possible only between states of opposite parity. For $M1$ transitions the combining terms must have the same parity.[1]

Taking into account the electroweak interaction, made possible in atoms by the neutral currents,[2] removes the restriction forbidding the simultaneous presence of $E1$ and $M1$ transitions between two terms. Their interference results in a difference in the absorption coefficients and refractive indices for right- and left-circularly polarized photons (see, for example, Refs. 3 and 4). The measurement of the resultant optical activity of the gas provides the basis for most of the experimental methods for the detection of parity violation in atoms.[5]

The interference between the $E1$ and $M1$ waves can induce anisotropy in the combining terms even under conditions of isotropic photon irradiation. This effect can be explained as follows. The $M1$ transition comes about in first order in the expansion of the matrix element of the interaction of the radiation (plane wave) with matter $\langle m|\mathbf{pA}\exp(\mathbf{kr})|\mathbf{n}\rangle$ in powers of $\mathbf{kr}$ ($\mathbf{p}$ is the momentum of the electron, $\mathbf{A}$ is the vector potential of the wave, $\mathbf{k}$ is the wave vector). To $E1$ corresponds the zero-order term in the expansion. Taking thus into account $M1$ transitions is nothing else but taking into account space dispersion. Under such condition the permittivity of the gas "becomes a tensor (and not scalar) even in an isotropic medium".[6]

We shall trace the mechanism for the formation of polarization moments on the example of a gas of two-level atoms (see Fig. 1). We assume that the levels m and n have the same angular momentum J and that the $E1$ transition between them is allowed. The Hamiltonian for the system in the rotating field representation has the form:

$$\hat{H}=\hat{D}+\hat{V}_M+\hat{V}_S. \qquad (1)$$

$\hat{D}$ and $\hat{V}_M$ are the operators of $E1$ and $M1$ interaction of the radiation with the atom; $\hat{V}_S$ is the pseudoscalar T-invariant operator of the weak interaction of the optical electron with the nucleons of a spinless nucleus.[3,4]

In the first stage we consider the interaction of the gas with a plane circularly polarized wave (for example, right circularly polarized). We choose the $\mathbf{z}$ axis in the direction of the vector $\mathbf{k}$. The matrix elements of the operators in (1) in the κ_q representation (the irreducible spherical tensors representation) are determined in the standard manner:[7]

$$\begin{aligned}
&D_{mn}(1,\sigma)=-dE_\sigma\exp\{i(\Omega t+\mathbf{kr})\},\\
&V_{Mj}(1,\sigma)=-\mu_j(H_\sigma\exp\{i(-\omega t+\mathbf{kr})\}+\text{c.c.}),\\
&V_{Smn}(0,0)=iS\exp(i\omega_{mn}t),\\
&\Omega=\omega_{mn}-\omega,\quad j=(m,n).
\end{aligned} \qquad (2)$$

E_σ and H_σ are the circular electric and magnetic components of the wave connected by Maxwell's equations; iS is the imaginary matrix element of the operator $\hat{V}_S$; ω_{mn} is the transition frequency; ω is the frequency of the radiation; μ_m, μ_n and d are the reduced magnetic dipole moments of the m-th and n-th levels and the $m-n$ transition electric dipole moment respectively. The matrix elements connected with the electromagnetic field form the components of a rank 1 spherical tensor (vector). The matrix elements of $\hat{V}_S$ give a scalar, more precisely—pseudoscalar.

The formation of anisotropy on degenerate levels is easy to see from the scheme in Fig. 1. The $E1$ transition with $\Delta M=1$ (M is the component of J along the $\mathbf{z}$ axis) connects the levels m and n, the $M1$ transition proceeds between magnetic sublevels of the level m and also changes M by unity, the weak interaction mixes the levels m and n without changing M and completes the process of the formation of a coherent coupling of the magnetic sublevels of the level n. The resultant change in M equals two, giving rise to alignment—the element of the density matrix $\rho_{nn}(2,\pm 2)$. The level m is aligned similarly.

In calculating $\rho_{jj}(2,\pm 2)$ and other elements of the density matrix it should be noted that, in contrast to $E1$ transitions, the $M1$ and S transitions are not individually resonant. But it is possible to select a combination of them responsible for stationary solutions of the system of equations for the density matrix. This results in an effective already resonant vector operator responsible for the $M1$ transition:

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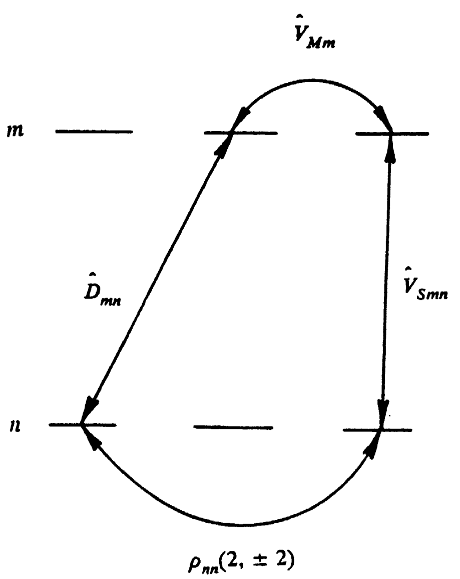

FIG. 1. The mechanism for the formation of alignment of a degenerate level under the action of circularly polarized radiation and P-odd exchange.

$$B_{mn}(1,\sigma) = -i\mu H_\sigma \exp\{i(\Omega t + \mathbf{kr})\},$$

$$\mu = \frac{\mu_B S(g_m + g_n)}{\omega_{mn}\sqrt{2J+1}}, \tag{3}$$

μ_B is the Bohr magneton; g_m and g_n are the g factors of the levels. The operator $B(1,\sigma)$ (we omit the indices m, n) is equal to the matrix elements of $M1$ transitions for the mixed by the Hamiltonian $\hat{V}_S$ levels m' and n' with indefinite parity.

To first approximation in intensity in the relaxation constants model we can obtain an expression for the polarization moments of the levels:[7]

$$\rho_{nn}^{(1)}(k,q) = \frac{6\Gamma \begin{Bmatrix} 1 & 1 & \kappa \\ J & J & J \end{Bmatrix} I(\kappa,q)(N_m - N_n)(-1)^{2J}}{\sqrt{2J+1}(\Gamma^2 + (\Omega - \mathbf{kv})^2)\Gamma_{\kappa n}},$$

$$\rho_{mm}^{(1)}(\kappa,q) = -\frac{\rho_{nn}^{(1)}(\kappa,q)\Gamma_{\kappa n}}{\Gamma_{\kappa m}}. \tag{4}$$

Γ, $\Gamma_{\kappa m}$ and $\Gamma_{\kappa n}$ are the relaxation constants of the electric dipole transition moment and the rank κ polarization moments of the levels m and n; $\{\cdots\}$ is the $6j$-symbol; N_m and N_n are the population distributions of the levels in velocity; $I(\kappa,q)$ is the polarization tensor defined as the direct product of spherical vectors $D(1,\sigma) \otimes D^*(1,\sigma)$ and $D(1,\sigma) \otimes B^*(1,\sigma)$.

For circular polarization the following components of $I(k,q)$ are different from zero:

$$I(0,0) = -d^2W/\sqrt{3}, \quad I(1,0) = d^2W/\sqrt{2},$$

$$I(2,0) = -d^2W/\sqrt{6}, \quad I(2,\pm 2) = \pm i\mu dW. \tag{5}$$

W is the intensity of the wave. The components $I(2,\pm 2)$ are the result of interference of $E1$ and $M1$ amplitudes for transitions between levels with indefinite parity. In view of the helicity nature of the space structure of n' or m',[8] the imaginary alignment $\rho_{jj}(2,\pm 2)$ also exhibits helicity.

It is not hard to see that the values of $I(\kappa,q)$ are the same for right and left circularly polarized radiation and do not change upon reversing the direction of the vector k.

In averaging over directions one should note that the value of $\rho_{jj}(2,\pm 2)$ in the new system of coordinates is determined by the projection of the plane of rotation of the **E** and **H** fields onto the XY plane and is independent of the azimuth angle φ. For $\rho_{jj}(\kappa,0)$, connected with $E1$ transition only, a dependence on φ survives, since φ specifies the incline of the plane in which the oscillations of the **E** vector take place when the polar angle is nonzero.

As a result of the averaging the polarization tensor, connected with $E1$ transitions only, reduces to the scalar $I(0,0)$, while taking into account $M1$ transitions produces helical alignment responsible for the tensor part of the dielectric permeability of the medium.[6] If the gas is irradiated by light due to spontaneous relaxation then the expression for the alignment should be averaged over Ω. From the symmetries of the expressions it is evident that the result of the averaging is nonzero.

If the direction of observation is chosen along the axis X, and the external magnetic field is directed along the axis Z, then the formation of helical alignment can be detected by the method of optomagnetic resonances (OMR),[9,10] sensitive to just the anisotropy of the medium. In the new system of coordinates the nonzero components of alignment are the following:

$$\rho_{jj}^{(1)}(2,\pm 2) \Rightarrow \rho_{jj}^{(1)}(2,\pm 1)$$

$$= \frac{i6\Gamma \begin{Bmatrix} 1 & 1 & 2 \\ J & J & J \end{Bmatrix} (N_i - N_j)\mu dW \cdot (-1)^{2J}}{(\Gamma^2 + (\Omega - \mathbf{kv})^2)\sqrt{2J+1}(\Gamma_{2j} \pm i\Delta_j)}, \tag{6}$$

Δ_j is the Larmor frequency.

In second order in the radiation intensity, $\rho_{jj}(2,\pm 1)$ from one level is transferred to another due to pure electric dipole interaction:

$$\rho_{mm}^{(2)}(\kappa,q) = \frac{2\sqrt{3}I(0,0)\Gamma}{(\Gamma_{\kappa m} + iq\Delta_m)(\Gamma^2 + (\Omega - \mathbf{kv})^2)} \left[\frac{\rho_{mm}^{(1)}(\kappa,q)}{2J+1} + \frac{\rho_{nn}^{(1)}(\kappa,q)(\kappa(\kappa+1) - 2J(J+1))}{2J(J+1)(2J+1)} \right]. \tag{7}$$

A similar transfer process takes place also for the lower level.

The possibility of optical transfer of coherence is mentioned in Ref. 11. This effect is exceptionally important for the detection of helical alignment. Let the gas have one more level l, with an allowed $E1$ transition $l-m$, on which the anisotropy of the gas will be detected. Then the ratio of the OMR amplitude to the absorption in the $l-m$ transition is proportional to the ratio of the total number of anisotropically excited atoms $\rho_{mm}(2,\pm 1)$ to the difference in the populations $N_m - N_l$. In second order in W into $\rho_{mm}^{(2)}(2,\pm 1)$ enters the alignment $\rho_{nn}^{(1)}(2,\pm 1)$, proportional to the population of the level n. If that level is strongly populated and metastable, then the effect of $\rho_{nn}^{(1)}(2,\pm 1)$ on the OMR, detected in the $l-m$ transition, will be enhanced by the ratio $(N_n\Gamma_{2m})/(N_m\Gamma_{2n})$. The enhancement coefficient is the larger the weaker the level m is populated. The detected OMR will be narrow and will have anomalous (with inverted symmetry) amplitude—frequency characteristics, observed in neon in Refs. 9 and 10.

The properties of OMR due to imaginary $\rho_{jj}(2,\pm 1)$ are discussed in considerable detail in Ref. 10. However the following circumstance was left out there. The $\rho_{jj}(2,\pm 1)$ are responsible for the off-diagonal components of the permittivity tensor. Therefore in the formation of the OMR dichroism and birefringence, induced by the transverse magnetic field, participates the product $E_zE_y^*$ (here E_i are the cartesian components of the electric field of the probing radiation). If the probing radiation is circularly polarized then the sign of the product $E_zE_y^*$ changes with a change in the polarization from right to left. Then the OMR-dichroism should change sign, while the OMR-birefringence should not change sign, upon change of polarization type. (This circumstance was indicated by K. I. Gus'kov.) According to the data of Ref. 10 the anomalous OMR-birefringence due to $\rho_{jj}(2,\pm 1)$ changed sign. And this can be understood if in the formation of $\rho_{jj}(2,\pm 1)$ there is participation of a pseudoscalar. The change in the type of circular polarization is equivalent to mirror imaging, under which a pseudoscalar changes sign, compensating the sign change of $E_zE_y^*$.

In this manner the totality of facts published in Refs. 9 and 10 indicates that the narrow anomalous OMR-birefringence in the transition $3s_2$–$2p_4$ due to $\rho_{jj}(2,\pm 1)$ is connected with parity violation effects in the neon system of terms. If the reason for the OMR being narrow is the metastable level $1s_5$, then the relatively large amplitude of the resonance (10^{-7}) could be caused by enhancement effects due to higher population of the $1s_5$ level and its long relaxation. According to the data of Ref. 12 the ratio of the populations of the levels $1s_5$ and $2p_4$ amounts to 10^5. The ratio of the relaxation constants is ~ 20, which gives the more realistic estimate of 10^{-13} for the contribution of the parity nonconservation effect into the anisotropy of the $1s_5$ level.

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